METHOD FOR OPTIMIZING PRINTING OF AN ALTERNATING PHASE SHIFT MASK HAVING A PHASE SHIFT ERROR

Field of the Invention

5   This invention relates generally to photolithography and in particular to a method for optimizing printing of an alternating phase shift mask having a phase shift error.

Background of the Invention

         Semiconductors are now produced having several million transistors per die.

10   To fit all of these devices on a single die, feature sizes must be minute. For example, a width of interconnect lines and a spacing between such lines needs to be very small. Accordingly, advances in semiconductor manufacturing allowing for more dense devices have resulted in the need for accurate, high resolution photolithography.

15   In general, photolithography involves transferring a mask pattern from a mask reticle onto a photoresist-coated substrate. The transfer is done using an imaging lens system and a beam of light. The reticle is often made from a slice of transparent quartz. The mask pattern on the reticle is a design that can be made up of opaque chromium regions and transparent quartz regions. If the beam of light is

20   composed of coherent light rays, the mask pattern would be transferred exactly to the coated substrate.

         However, light rays are not coherent and diffraction causes light to bend as it passes through the pattern reticle. Diffraction becomes significantly problematic when the chromium and transparent regions on the mask reticle are near in size to

25   the wavelength of a beam of light. When diffraction occurs, regions on the coated substrate which should be dark receive the diffracted light. Thus, the pattern is adversely affected by diffracted light.

Phase shifting lithography is a method of reducing the effects of light diffraction. Adjacent transparent quartz regions of a pattern on an alternating phase shifting mask, which are separated by an opaque region, are created such that the phase of the light going through one of the transparent regions is shifted, or delayed,

5   180 degrees from that of light going through an adjacent transparent region. Shifting light by 180 degrees mitigates the problem caused by the diffraction.

When light is diffracted from two adjacent transparent regions onto a dark region of the substrate, the diffracted light cancels each other out. The cancellation occurs due to the additive nature of light rays: two rays having a phase difference of

10   180 degrees result in no light. Thus, shifting the phase of the light helps to ensure that the dark region remains dark.

One way to accomplish phase shifting is to etch every other transparent region on the quartz mask reticle so that light traveling through the etched regions will exit the reticle one-half wavelength behind light traveling through the unetched

15   regions. However, it is difficult to etch the quartz reticle so that light has a phase shift of exactly 180 degrees. When a phase of light is not fully shifted 180 degrees, the alternating phase shifting mask has a phase error and diffraction remains a problem. Generally, when an alternating phase shifting mask has a phase shift error, the mask is discarded.

20   For the reasons stated above, and for other reasons stated below which will become apparent to those skilled in the art upon reading and understanding the present specification, there is a need in the art to mitigate the problems of a phase shift error present in an alternating phase shifting mask.

25   **Summary of the Invention**

The above mentioned problems associated with diffraction caused by an alternating phase shifting mask having a phase shift error are addressed by the

2

present invention which will be understood by reading and studying the following specification.

An image from an alternating phase shifting mask having a phase shift error is printed using off-axis illumination. Shooting the mask off-axis compensates for

5 the phase shift error. In operation, an illuminator providing a light source simulates the image for determining off-axis illumination parameters that will optimize printing of the image at best focus. Once the parameters establishing best focus are optimized, the image is shot. Because the phase error is compensated by off-axis illumination, the alternating phase shifting mask may be utilized instead of having to

10 discard it. In addition, the method of varying off-axis illumination parameters to compensate for a phase shift error permits an alternating phase shifting mask to be shot at two different wavelengths. An alternating phase shifting mask initially configured for operation at a first wavelength using on-axis illumination may be shot at a lower second wavelength because the phase shift error associated with the

15 second wavelength is compensated by shooting the mask off-axis.

In one embodiment, a photolithography system comprises an alternating phase shifting mask having a phase shift error, and an illuminator configured for off-axis illumination wherein the illuminator performs image simulations using the alternating phase shifting mask for defining off-axis illumination parameters to

20 compensate for the phase error.

In another illustrative embodiment, a photolithography system comprises an alternating phase shifting mask having a phase shift error, an illuminator providing a light source, and a means for controlling the light source to optimize printing of the alternating phase shifting mask. The means for controlling the light source utilizes

25 off-axis illumination.

In yet another embodiment, a method to optimize printing of an alternating phase shifting mask having a phase error comprises the steps of configuring an illuminator for off-axis illumination, performing simulations of an image on the

3

alternating phase shifting mask, and adjusting off-axis illumination parameters based upon the simulations.

In a still further embodiment, a method to optimize printing of an alternating phase shifting mask having a phase error comprises the steps of providing an

5   alternating phase shifting mask having a phase shift error, providing an illuminator having a light source, performing simulations on an image of the alternating phase shifting mask, and providing a means for controlling the light source to optimize printing of the alternating phase shifting mask based upon the simulations. The step of providing an illuminator utilizes off-axis illumination.

10   In another embodiment, a method of printing an image from an alternating phase shifting mask using two different wavelengths comprises the steps of providing an alternating phase shifting mask, providing a first illuminator having a light source at a first wavelength, printing an image on the alternating phase shifting mask, providing a second illuminator having a light source at a second wavelength,

15   configuring the second illuminator for off-axis illumination, performing simulations of the image on the alternating phase shifting mask, adjusting off-axis illumination parameters based upon the simulations, and printing an image on the alternating phase shifting mask.

In yet another embodiment, a method of printing an image from an

20   alternating phase shifting mask using an illuminator operating at a shorter wavelength from what the mask was initially designed for comprises the steps of providing an alternating phase shifting mask, providing an illuminator having a light source, configuring the illuminator for off-axis illumination, performing simulations of the image on the alternating phase shifting mask, adjusting off-axis illumination

25   parameters based upon the simulations, and printing an image on the alternating phase shifting mask.

Optimizing printing of an image from an alternating phase shifting mask having a phase shift error is accomplished using off-axis illumination. By first simulating the image, parameters with respect to off-axis illumination are optimized to compensate for the phase shift error. In different embodiments of the invention,

5 optical characteristics of the mask supporting transparency, opaqueness, partial opaqueness, and phase shifting effects of varying scope and combinations are described. Still other and further embodiments, aspects and advantages of the invention will become apparent by reference to the drawings and by reading the following detailed description.

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Brief Description of the Drawings

Figure 1A illustrates a cross sectional view of a conventional mask.

Figure 1B illustrates a cross sectional view of an alternating phase shifting mask.

15 Figure 2 illustrates a photolithographic system incorporating an off-axis illuminator with an alternating phase shifting mask.

Figures 3-5 are aerial simulations at varying defocus parameters using on-axis illumination with an alternating phase shifting mask having a phase shift error.

Figures 6-8 are aerial simulations at varying defocus parameters using off-

20 axis illumination with an alternating phase shifting mask having a phase shift error.

Detailed Description of the Invention

In the following detailed description of the invention, reference is made to the accompanying drawings which form a part hereof, and in which is shown, by

25 way of illustration, specific embodiments in which the invention may be practiced. In the drawings, like numerals describe substantially similar components throughout the several views. These embodiments are described in sufficient detail to enable

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those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the present invention. The terms wafer and substrate used in the following description include any structure having an exposed surface with which to

5   form the integrated circuit (IC) structure of the invention. The term substrate is understood to include semiconductor wafers. The term substrate is also used to refer to semiconductor structures during processing, and may include other layers that have been fabricated thereupon. Both wafer and substrate include doped and undoped semiconductors, epitaxial semiconductor layers supported by a base

10   semiconductor or insulator, as well as other semiconductor structures well known to one skilled in the art. The term conductor is understood to include semiconductors, and the term insulator is defined to include any material that is less electrically conductive than the materials referred to as conductors. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the

15   present invention is defined only by the appended claims, along with the full scope of equivalents to which such claims are entitled.

The present invention is a method of printing an image from an alternating phase shifting mask having a phase shift error using off-axis illumination. The image is first simulated using off-axis illumination at various parameters to

20   determine best focus of the image. Once the off-axis illumination parameters are optimized, the image is shot onto a substrate. Focusing of the image is thus accomplished using off-axis illumination from empirical data provided by the simulations run on the mask. In addition, the method of varying off-axis illumination parameters to compensate for a phase shift error permits an alternating

25   phase shifting mask to be shot at two different wavelengths.

In reference to Figures 1A-B, a conventional mask and an alternating phase shifting masked are illustrated, respectively. A portion of a conventional

photolithographic mask 3 is depicted in cross-sectional format in Figure 1A. The mask 3 consists of a uniformly thick quartz plate 11 and a thin, chromium metal layer 12 which has been selectively etched so as to create a pattern of opaque regions 13 and transparent regions 14.

5   The conventional mask 3 is converted to an alternating phase shifting mask 5, as illustrated in Figure 1B, by masking every other transparent region 14 with photoresist 21, and then subjecting the alternating phase shifting mask 5 to a plasma etch. This etching is performed until the unmasked transparent regions 22 are relieved to a depth such that rays of light from a coherent source pass through the

10   unetched transparent regions 23 a predetermined wavelength behind rays of light from the same coherent source passing through neighboring etched transparent regions 22. Varying the depth 8 of the etched regions 22 determines the amount of phase shift. The mathematics employed in the construction of an alternating phase shifting mask are well known in the art and will not be discussed herein.

15   When light passes through the etched regions 22 in an alternating phase shifting mask, a 180 degree shift in phase is achieved with respect to a phase of light passing through the unetched transparent regions 23. Although such a process works acceptably in principle, the plasma etch damages the optical characteristics of the quartz so that transmittance through the etched transparent regions 22 is reduced

20   as compared to the transmittance through unetched transparent regions 23. A resulting error in a phase shift has a somewhat less than adequate cancellation effect on neighboring diffraction patterns on a surface exposed by the alternating phase shifting mask 5.

       Figure 2 illustrates a photolithographic system 70 incorporating an

25   illuminator 72 with an alternating phase shifting mask 5. The photolithographic system 70, such as a stepper, consists of the alternating phase shifting mask 5 illustrated in Figure 1B inserted in a light path of the illuminator 72 to control a

wafer image resulting on a substrate 80 structure. Off-axis illumination is achieved

by the illuminator 72 having a restrictor means 74 for controlling the light 76

provided by the illuminator 72. The illuminator 72 is a source for incoming light

76, such as ultra violet (UV) light. The light 76 is directed through the restrictor

5   means 74, the alternating phase shifting mask 5, and an optics lens 78 before falling

onto a photoresist layer 82 overlying a conductive layer 84 which overlies the

substrate structure 80.

By shining the light 76 through the alternating phase shifting mask 5, a light

pattern is cast upon the semiconductor wafer 84 or a portion thereof which is

10   covered with the photoresist 82 or a similar material. The portion of this photoresist

material 82 which is under the mask and subject to the light 76 is accordingly

hardened due to the exposure it receives. If a negative photoresist material 82 is

used, a portion of the photoresist material 82 not exposed to the light 76 is removed

to expose portions of the substrate structure 80 while the remaining photoresist 82

15   protects unexposed portions of the substrate during subsequent processing steps.

Subsequently, a suitable well-known solvent material etches away the unhardened

portion of the photoresist 82 to form an integrated circuit.

The restrictor means 74 is generally an adjustment on the illuminator 72

wherein the light 76 provided by the illuminator 72 is varied with respect to an

20   optical axis of the illumination system 70. By controlling a source of the light 76

via the restrictor means 74 before reaching the alternating phase shifting mask 5,

off-axis illumination is achieved. Utilization of off-axis illumination improves

process latitude and improves a depth of focus of an image on the alternating phase

shifting mask 5 as compared to conventional illumination techniques when the

25   alternating phase shifting mask 5 has a phase shift error.

There are a various methods to achieve off-axis illumination. The restrictor

means 74 referenced in Figure 2 is a general reference applicable to a variety of

methods that may be utilized for achieving off-axis illumination. Methods of achieving off-axis illumination are well known to one skilled in the art.

By way of illustration of the present invention, the restrictor means 74 illustrated in Figure 2 is a ring having an inner radius 90 and an outer radius 92

5   wherein light 76 is not passed within the inner radius 90. Light 76 is passed only between the area inside of the outer radius 92 and outside the inner radius 90. The inner radius 90 is referred to as sigma in. The outer radius 92 is referred to as sigma out. By varying the sigma in 90 and the sigma out 92 parameters, depth of focus (DOF) of an image on the alternating phase shifting mask 5 may be varied. If the

10   alternating phase shifting mask 5 has a phase shifting error, then the sigma in and sigma out parameters are selected to compensate for the phase shift error. Another parameter effecting image is defocus. To select the proper defocus value, a mask is shot at different defocus values for determining which one provides the best image.

An image on the alternating phase shifting mask 5 is simulated using off-

15   axis illumination at various parameters (e.g., sigma in, sigma out and defocus) to determine best focus of the image. Empirical data provided by the one or more simulations permits the photolithographic system 70 to optimize the off-axis illumination parameters.

Effects of an alternating phase shifting mask 5 having a phase shift error is

20   illustrated in Figures 3-5 using on-axis illumination and in Figures 6-8 using off-axis illumination. Instead of the alternating phase shifting mask 5 having a desired phase shift of 180 degrees, the alternating phase shifting mask 5 has a phase shift of 90 degrees. A 90 degree phase error is a worst case scenario for purposes of illustrating compensation provided by shooting the alternating phase shifting mask 5

25   using off-axis illumination. While a 90 degrees phase shift error is an extreme example, an alternating phase shifting mask 5 having a phase shift error less than 90 degrees is also compensated by using off-axis illumination.

9

Figures 3-5 are aerial simulations at varying defocus parameters using on-axis illumination with the alternating phase shifting mask 5 having a phase shift error of 90 degrees. A numerical aperture (NA) remains a constant 0.54 for each of the three figures. Sigma also remains a constant 0.35. Since on-axis illumination is

5   utilized, the restrictor means 74 illustrated in Figure 2 is more like a disk. Sigma represents the radius of this disk.

The aerial images are simulated line-in-space wafer image patterns as if a mask pattern contains equidistant chrome lines separated by transparent regions. At best focus, dark lines should be identical in size and spacing. Referring to Figure 3,

10   a simulated image 105 is shown with a defocus of 0 μm. Defocus and best focus are interchangeable terms.

Dark lines 110 represent low levels of intensity and gray areas 115 represent high intensity levels. When printed on a wafer, the dark lines 110 represent lines and the gray areas 115 represent spaces. Because simulation 105 is performed at

15   best focus, the dark lines 110 are nearly equidistant from one another. However, the dark lines 110 gradually fade due to the diffraction caused by the 90 degree phase error.

A simulated image 205 in Figure 4 illustrates the worsening effects of increasing the defocus value from 0 μm to 0.5 μm. The simulated image 205 does

20   not reflect equal line widths and equal spacings between the lines, as reflected in Figure 3. Because of the 90 degree phase shift error, the image gets more distorted as it gets out of focus. The dark lines 210 remain constant but the spaces alternate in size between narrow spaces 210 and wide spaces 220.

As the defocus value is further increased to 1.0 μm, as illustrated in Figure 5,

25   two of the spaces disappear and the remaining two spaces 315 are wider. With the larger defocus value, the lines 310 have carried over to the point of covering a space.

Every other space has thus disappeared because of a combination of the defocus value and the 90 degree phase shift error.

If there is no phase error, the lines 310 and spaces stay at exactly the same location. When an image is moved out of focus at a zero phase shift error, the lines

5   do not move but the image gets blurry from a change in contrast. Therefore, as illustrated in Figures 3-5, a combination of selected defocus values and a 90 degree phase shift error creates a problem for the alternating phase shifting mask 5 using conventional illumination techniques.

Figures 6-8 are aerial simulations of the same mask layout as in Figures 3-5

10   except using off-axis illumination. Instead of having a constant sigma of 0.35, the restrictor means 74 has a sigma in radius 90 of 0.4 μm and a sigma out radius 92 of 0.62 μm wherein light 76 is not passed within the inner radius 90. Light 76 is passed only between the area inside of the outer radius 92 and outside the inner radius 90. By varying the sigma in 90 and the sigma out 92 parameters, a depth of

15   focus (DOF) of the image on the alternating phase shifting mask 5 is varied.

To be consistent with Figures 3-5, the defocus is increased from 0 μm in Figure 6, to 0.5 μm in Figure 7, and to 1.0 μm in Figure 8. The phase shift error for these three figures remains at 90 degrees and the numerical aperture (NA) remains at 0.54. The sigma in 90 and sigma out 92 values used in Figures 6-8 serve as an

20   illustration of the present invention and such values vary depending on a given phase shift error.

The aerial images presented in Figure 6-8 are simulated line-and-space wafer image patterns as if a mask pattern contains equidistant chrome lines separated by transparent regions. At best focus, dark lines should be identical in size and

25   spacing. Referring to Figure 6, a simulated image 405 is shown with a defocus of 0 μm. As previously stated, defocus and best focus are interchangeable terms.

11

Dark lines 410 represent low levels of intensity and gray areas 415 represent high intensity levels. When printed on a wafer, the dark lines 410 represent lines and the gray areas 415 represent spaces. Light areas 415 are considerably more uniform than their counterpart light areas 115 as illustrated in Figures 3. This is a

5 result of off-axis illumination which improves process latitude and improves the depth of focus of the image on the alternating phase shifting mask 5 as compared to conventional illumination techniques.

A simulated image 505 in Figure 7 illustrates the effects of increasing the defocus value from 0 μm to 0.5 μm. The simulated image 505 does not reflect equal

10 line widths and equal spacings between the lines, but light areas 515, 520 are considerably more uniform than their counterpart light areas 215, 220 of Figure 3 due to the off-axis illumination.

As the defocus value is further increased to 1.0 μm, as illustrated in Figure 8, spaces 615 are considerably more uniform than the counterpart spaces 315 in Figure

15 5. Using off-axis illumination with the larger defocus value, the lines 610 have not carried over to the point of covering a space, as was the result with on-axis illumination.

The simulated images 405, 505, and 605 of Figures 6-8 thus use off-axis photolithography in combination with the same alternating phase shifting mask 5

20 used in Figures 3-5 to improve process latitude and improve the depth of focus of the image on the alternating phase shifting mask 5 as compared to conventional illumination techniques. Light areas 415, 515/520, and 615 (representing spaces) corresponding to Figures 6-8, respectively, are considerably more uniform than their counterpart light areas 115, 215/220, and 315 as illustrated in Figures 3-5,

25 respectively. Although Figure 8 has a high defocus value of 1 μm, simulation image 605 is only slightly degraded. Thus, the distortion caused by a defocus value and a phase shift error has been greatly mitigated. The use of off-axis photolithography in

12

combination with alternating phase shifting masks improves the results from traditional phase shift systems when the alternating phase shifting mask 5 has a phase error.

   The simulated images illustrated in Figures 3-8 result from a phase shift
5 error of 90 degrees, which is a worst case scenario. Typically, a phase error will be considerable smaller. For example, the alternating phase shifting mask 5 may have a phase error of 10 degrees. Rather than having a sigma in 90 and a sigma out 92 of 0.4-0.62 μm, a smaller sigma in 90 and sigma out 92 may be used, such as 0.05-0.35 μm. Hence, the results from using off-axis photolithography with an alternating
10 phase shifting mask would readily support a smaller level of image degradation.

   Other embodiments of the invention include using the alternating phase shifting mask 5 at two different wavelengths. For example, an alternating phase shifting mask 5 is built with a 180 degree phase shift for an I-line light source operating at 360 nm. The alternating phase shifting mask 5 is shot using on-axis
15 photolithography. Subsequently, the same alternating phase shifting mask 5 is shot using off-axis from an ultra-violet (UV) light source operating at 465 nm. The use of the later illuminator is possible because off-axis illumination compensates for the phase shift error at the lower frequency light source. Thus, the same alternating phase shifting mask 5 is used for two different wavelengths.

20   Although an alternating phase shifting mask was used throughout the description, the same optimization using off-axis illumination is also applies to attenuating phase shifting masks. Combining the method of the present invention would improve the fidelity of the resultant image.

   Although specific embodiments have been illustrated and described herein, it
25 will be appreciated by those of ordinary skill in the art that any arrangement which is calculated to achieve the same purpose may be substituted for the specific

embodiment shown. This application is intended to cover any adaptions or variations of the present invention.

Conclusion

Optimizing printing of an image from the alternating phase shifting mask 5 having a phase shift error is accomplished using off-axis illumination 70. By simulating the image using varying off-axis illumination parameters, optimized parameters are determined for compensating for the phase shift error. Once the off-axis illumination parameters are optimized, the image is shot. In addition, the method of varying off-axis illumination parameters to compensate for a phase shift error permits the alternating phase shifting mask to be shot at two different wavelengths. In one embodiment, a photolithography system comprises the alternating phase shifting mask having a phase shift error, an illuminator providing a light source, and a means for controlling the light source to optimize printing of the alternating phase shifting mask. The means for controlling the light source utilizes off-axis illumination. In another embodiment, a method to optimize printing of the alternating phase shifting mask having a phase error comprises the steps of configuring an illuminator for off-axis illumination, performing one or more simulations of an image on the alternating phase shifting mask, and adjusting off-axis illumination parameters based upon the simulations. In yet another embodiment, a method of printing an image from the alternating phase shifting mask using an illuminator operating at a shorter wavelength from what the mask was initially designed for comprises the steps of providing the alternating phase shifting mask, providing an illuminator having a light source, configuring the illuminator for off-axis illumination, performing one or more simulations of the image on the alternating phase shifting mask, and adjusting off-axis illumination parameters based upon the simulations, and then printing an image on the alternating phase shifting mask.

14